3D printing of fibre cement-based materials: fresh and rheological performances

Marine Rubio, M Sonebi, S Amziane

3D PRINTING OF FIBRE CEMENT-BASED MATERIALS: FRESH AND RHEOLOGICAL PERFORMANCES

M. Rubio[1,2], M. Sonebi[1*], S. Amziane[2]

[1] Queen's University Belfast, School of Natural and Built Environment., Belfast, BT7 1NN, UK

[2] Université Blaise Pascal, Institut Pascal, Polytech Clermont-Ferrand, 63174, Aubière, France

*Corresponding author; e-mail: m.sonebi@qub.ac.uk

Abstract

The aim of this paper is to investigate the effect of different mix composition on fresh and rheological properties of a printable mortar. For the mix design, two binders such as fly ash (FA), and silica fume (SF) were used with cement and sand for a water/binder ratio of 0.50. Polypropylene fibres (PP), superplasticizer (SP), and viscosity modifying agents VMA (Diutan gun and nano-clay) were used in the investigation.

The results show that adding 24% of fly ash and 8% Silica fume increased the yield stress, cohesiveness, and improved the structure homogeneity and stability which appeared to be an advantage to print layers. Indeed it reduced the fluidity, bleeding and the blockage of layers. Additionally, it also improved the passing ability through the extruder and showed a greater resistance to penetration.

The addition polypropylene fibres (0.2% to 0.6%) led to a higher yield stress, and cohesiveness of the mix. This is led to a stable mortar and kept the shape of layer under its own weight and sustained weight of successive layers. The incorporation of PP fibres reduced the time gap. Furthermore, high dosage of fibres can create more difficulties to extrude layers and led more drainage phenomenon which increased the stiffening of the mix. PP fibres might be efficient to print layers due to their small length and diameter which resulted in a dense and efficient network.

VMAs cause an important loss of workability and time gap which influenced the passing ability of the mix through the extruder. However a high dosage of SP increased also bleeding and segregation and may affect the stability and shape of the printable layers. Good correlations existed between slump flow results, penetration results and also yield stress.

Keywords:

3D printing; polypropylene fibres; penetration; slump flow; superplasticiser; viscosity modifying agent

1 INTRODUCTION

Inspired by the 3D printing with polymer materials, 3D printing opens new horizons to cement-based materials of the construction industry. As formworks represent 35-60% of the overall costs of concrete structures, it would be an important financial advantage to use this new technology. Besides, 3D printing in building structures without formworks permits to improve the construction rate and open to new architectural liberties. Replacing humans work by additive technology automated allows building in polluted zones or on planets as reported in the project of contour crafting with the construction of bases on the moon for the NASA [P.3D 2015]. Several applications were reported on applications and prototypes of 3D printing [Khoshenevis 2006] [Le 2012] [Alec 2016] [Scott 2016] [Alec 2016] [Lloret 2015].

Contour Crafting is currently the most effective method researchers have found so far. The concrete layers are poured out by robotic machines and can be used for small-scale industrial parts and building structures [Malaeb 2015].

The two previous pioneers of 3D printing concrete as companies were the Shanghai Company, WinSun [Wangler 2016]. It was reported that to 10 full scale houses have been printed in less than 24 hours with 3D printing concrete. The method is appealing by the low cost of each house, around 5000$ [Malaeb 2015]. The largest 3D printer has been created by the World's Advanced Saving Project launched in 2010 by the Italian Centro Sviluppo Progetti Company. It was 12 meters tall in a hexagonal shape [Wangler 2016].

Finally, HuaShang Tengda Company (China) has recently managed to incorporate reinforcements to its 3D printed concrete structure. In fact, they have printed a 400 m² villa around iron frameworks by using an original nozzle design. They first raised the complete steel bars and pipes complex of the house. Then, concrete has been printed over it with big scale 3D printer [Scott 2016].

The printability of fresh cement based materials is the ability of the layer to maintain itself and the weight of the layers subsequently deposited. The time gap between two deposited layers must be sufficiently long to provide adequate mechanical strength capable of sustaining the weight of the subsequently deposited layers and also short enough to provide an optimized bond strength and building rate. It appears that it's the shortest time gap which allows the stability of the structure during construction. The ability of the first layer to support itself and others layers is link to its rheology and more precisely to its yield stress [Perrot 2015].

The aim of this study is to evaluate the effect of different mix composition parameters included dosage of superplasticizer (SP), addition of fly ash (FA) and silica fume (SF), the dosage of polypropylene fibres (PP) and type of viscosity modifying agent (VMA) on fresh and rheological properties of a printable mortar.

2 EXPERIMENTAL PROGRAMME

Fresh properties of printed cement-based mortar compose of fly ash and silica fume, incorporating fibers (PP), viscosity modifying agent (VMA such as diutan gum, nano-clay) and superplasticizer were investigated.

The following properties of the mortars were examined: the slump flow, the penetration test, the rheological properties (yield value), and the extruded property. Moreover, the relationships between the fresh properties were evaluated.

2.1 Materials

The mortars were prepared with a fixed water-to-binder ratio (w/b) of 0.50. Portland cement CEMI 42.5N specified by BS EN 197-1: 2000 (specific gravity of 3.13) was used in all mixes. Fly ash from Scot ash ltd was added and conformed to BS EN 450-1:2005. Undensified silica fume (SF) were used with a percentage of 8% relative to the mass of cement. The percentage of SiO_2 was more than 90% and the specific surface area of SF was 17500 m^2/kg with a specific gravity of 2.2.

A synthetic polycarboxylate polymer-based superplasticiser (SP) with solid content of 30% and specific gravity of 1.05 was used.

Diutan gum was supplied by Kelco-crete which is an anionic polysaccharide gum as used as viscosity modifying agent (VMA1). It was used as powder at 0.05% (by mass of binder).

A second VMA Acti-gel208 nano-clay based composed of attapulgite-clay small needles with negative charges (VMA2) is used at 0.10% (by mass of binder).

Sand with maximum particle size of 1.18 mm was obtained by sieving oven-dried (at 105 ±5 °C) sand with particle size of 0–5 mm.

Polypropylene fibres (PP) having length 6 mm was used to improve cohesion, holding, mould-ability, and to limit the cracking of cementitious composites.

2.2 Mixing and testing procedure

The mortars were prepared with high-shear Hobart mixer in 2-L batches. Premixed solid components, i.e. cement, fly ash (if any), silica fume (if any) and sand, were mixed for 30 seconds at low speed (140 rpm). Next, water at temperature of 16 ±0.5 °C and SP were added together to the mixer and mixed for 30 seconds at a low speed (140 rpm). Then the mixer was stopped, any lumps of solids were crushed, fibres (if any) and VMA1 or VMA2 (if any) were added (within 1 min), and the mortar was mixed again for 2 min (4 min when VMA2 is added) at a high speed (285 rpm). Then VMA1 (if any) is added and the mortar is mixed 1 min at a low speed (140 rpm). The temperature of the mortar after mixing was 20 ± 1 °C. For all tests the timing is given from zero time – that is, the time when the cement particles first touch the mixing water.

The penetration test (cone plunger) was started at 6 min (immediately after the end of mixing – Fig. 1). After filling the cone mould with mortar in two layers, the cone plunger is adjusted in order to allowing the cone to just touch the surface of the mortar sample. Then the cone plunger is released allowing the plunger to penetrate into mortar paste under its own weight for 5 seconds. After 5 seconds, the penetration value is noted to the nearest millimetre.

Then the slump flow test was started at 10 min (Fig. 2). The dimensions of cone were 100 x 70x 60 mm. The cone-shaped mould was placed in the centre of a jolting table. After filling with mortar in two layers, the cone was gently lifted 15 times (approximately 30 s after finishing of placing of the grout). When the flow stopped, the spread of the mortar was measured with a ruler in two perpendicular directions. Finally, extrudability of mortar mixes is tested with the simple modified joint gun described in Fig. 3.

Rheological measurement was carried out with a computer-controlled vane viscometer (Haake VT550). At 6 ± 1 min, approx. 800 ml of the sample was introduced into a plastic container where the vane was plunged. After 30 s rest, the test was started and the mortar was sheared at different shear rates.

The two rheological parameters, yield stress (τ_0) and plastic viscosity (μ_p), were obtained from the modified Bingham model fitted to the experimental data (down-curve). The yield stress at a zero shear rate was extrapolated from the Bingham model. Unfortunately, as mortar mixes were too stiff to be characterized with the viscometer, a semi-empirical alternative is used to determine the yield stress using cylinder measurement (slump – Fig. 4, [Pashias 1996]) : $s' = 1 - 2\tau'_y(1 - 2\ln(2\tau'_0))$

where:

- Cylinder dimensions : h_0 = 138 mm and d_0 =64 mm
- s = h_0 - h with h_0 the initial height and h the final height
- s' = s/h deformation quantities are dimensionless
- $\tau'_0 = \tau_0/\rho m.g.h_0$ stress quantities are dimensionless

The test procedure is detailed in the following steps. The mould is placed centrally on the flow table and the mortar is introduced in two layers. Each layer is compacted with ten short strokes in order to have a uniform filling of the mould. The mould is maintained in place firmly during the filling. The excess of mortar is remove with the help of a palette knife. After 15 seconds the cone is gently and vertically lifted and the height of the spread mortar is measured (Fig. 4).

The weight of the mortar was measured in constant volume and the fresh density of the mortar was calculated.

The workability life is a crucial parameter which is influenced by the build-up rate of layers. It was measured by the time at which it reached a defined limit of stiffness or workability during the gun extrusion test.

The workability life test measuring the evolution of the consistency, yield stress and extrudability during time was performed beginning with the first measurement of the flow table test and penetrometer test, and then cylindrical slump test and extrudability test. After, these tests were repeated every fifteen minutes until the mortar was too stiff. These tests are interesting because it can indicate the printable length of the layer which influences the overlaying time gap between two layers.

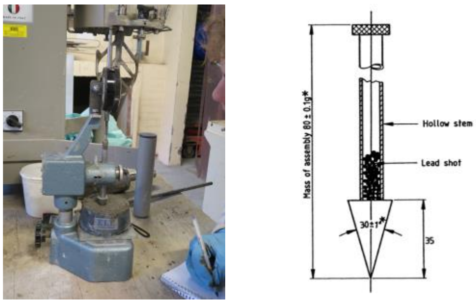


Fig. 1: Penetration test.

Fig. 2: Slump flow test

Fig. 3: Extrudability test

Fig. 4: Slump of cylinder test

3 MIX PROPRTIONS

Table 1 summaries the mix proportions of 3D mortars tested in this investigation. w/b ratio used was 0.50 and binder-to-sand ratio was 0.50. Four parameters were investigated: effects of fly ash as replacement of 24% (by mass of cement) and silica fume (8% replacement of cement), dosage of SP (0.275(1/2 SP) and 0.55% (SP) of binder), dosage of PP fibres (0.2% to 0.6%), and effect of type of VMA (% of binder by mass, VMA1, VMA2).

The diutan gum based VMA was added at 0.05% and the nano-clay based VMA was added at 0.1%. Then polypropylene micro fibres were added with a varying percentage at 0.2%(PP), 0.4%(2PP) and 0.6% (3PP) relative to the total batch volume in order to reduce the shrinkage and the deformation in plastic state.

4 RESULTS AND DISCUSSION

The purpose of the experimental program is to analyse the effect of different mix compositions on the rheological behaviour and fresh properties of a printable mortar by using simple tests (flow table test, cylindrical slump test, penetrometer test). The rheological parameters were evaluated by yield stress.

In this investigation, stiff mixes were tested by the rheometer and it caused some difficulties which due to the limitation of the rheometer. Therefore, the slump test as a simplified rheological test is adopted in order to estimate the static yield stress.

Tab. 1: Compositions of all mixes (kg/m^3)

	Cement	Water	Sand	FA	SF	VMA1 (%)	VMA2 (%)	SP (%)	PP
NO FA SP PP 100% cement	618	311	1233	-	-	-	-	0.55	1.2
SP PP	463	305	1208	144	-	-	-	0.55	1.2
SP 2PP	463	305	1208	144	-	-	-	0.55	2.4
SP 3PP	463	305	1208	144	-	-	-	0.55	3.6
1/2 SP PP	463	307	1208	144	-	-	-	0.275	1.2
1/2 SP 2PP	463	307	1208	144	-	-	-	0.275	2.4
1/2 SP 3PP	463	307	1208	144	-	-	-	0.275	3.6
SF SP PP	432	273	1228	146	75	-	-	0.55	1.2
SF SP 2PP	432	273	1228	146	75	-	-	0.55	2.4
SF 1/2 SP PP	432	259	1228	146	75	-	-	0.275	1.2
VMA1 SP PP	463	305	1208	144	-	0.05	-	0.55	1.2
VMA2 SP PP	463	305	1208	144	-	-	0.1	0.55	1.2
VMA2 SF SP PP	463	273	1228	144	75	-	0.1	0.55	1.2

4.1 Effect of binder on fresh and rheological properties of printed layers

Results of penetration and slump flow, obtained by flow table, composed of 100% of cement, 76% of cement and 24% of fly ash are plotted in Fig. 5.

Fig. 5 indicates a decrease of the slump flow values with the addition of fly ash. The surface area of fly ash is equal to 420 m²/kg which is slightly greater than the cement (370 m²/kg). Consequently, bleeding and segregation were reduced as more water is needed to cover the surface of these particles. A Higher amount of unburned carbons from FA might lead to a reduction of workability linked to the adsorption of SP [Sonebi 2006].

The results of the penetrometer (Fig. 5) indicate basically the same penetration with the addition of fly ash. There was no significant effect on penetration and the maximum of value of 39mm represents the limit of the penetration test; consequently it's difficult to observe the influence of fly ash on the penetration results. In this case the consistency mortar was too soft to be analysed with the penetrometer. Fig. 6 shows that adding FA improved the shape of printed layers.

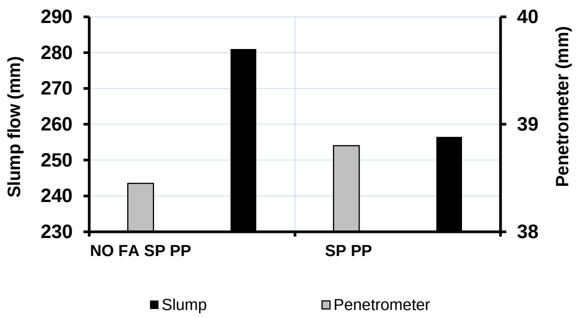


Fig. 5: Effect of FA on slump flow and penetration

Fig. 6: Layers of 3 D printing with and without FA

With the incorporation of silica fume, Fig. 7 indicates a reduction in the slump flow values for both mixes made with PP and 2PP. Additionally, it can be observed an increase of the static yield stress (mix made with 2PP) which indicated the influence of the very reactive silica fume on the workability of the mortar mix (Fig. 8).

Surface area of SF (BET) was 17500 (m^2/kg) which is really greater than the cement and fly ash (respectively equal to 370 m²/kg and 370m²/kg). Furthermore, at the fresh state, silica fume permits also to the cement based material to be more cohesive (less segregation and bleeding) which increases the yield stress and the fluidity of a portion of the mix isn't altered and doesn't allowed a greater spread compared to a mix containing fly ash [Sonebi 2010] [Sonebi 2015]. Additionally, as silica fume is a very reactive pozzolanic material, it reduces delay in setting [Sonebi 2015].

Silica fume counterbalances the addition of superplasticiser and fly ash (retarder effect). It seems that SF permits to obtain quickly a stable structure of extrudable mortar which is very interesting for the 3D printing. This resulted to keep after the extrusion, the shape of the layer under its own weight and under successive layers weight without degrading the extrudability (Fig. 8).

The results of the penetrometer have the same trend compared to the results of slump flow values as it can be noticed in Fig. 7. A reduction of the penetration with the addition of SF is highlighted (for both mixes SP-PP and SP-2PP). The penetrometer results indicated that there was an improvement of the cohesiveness of the mix containing SF and improving the shape of 3D printing layers (Fig. 8).

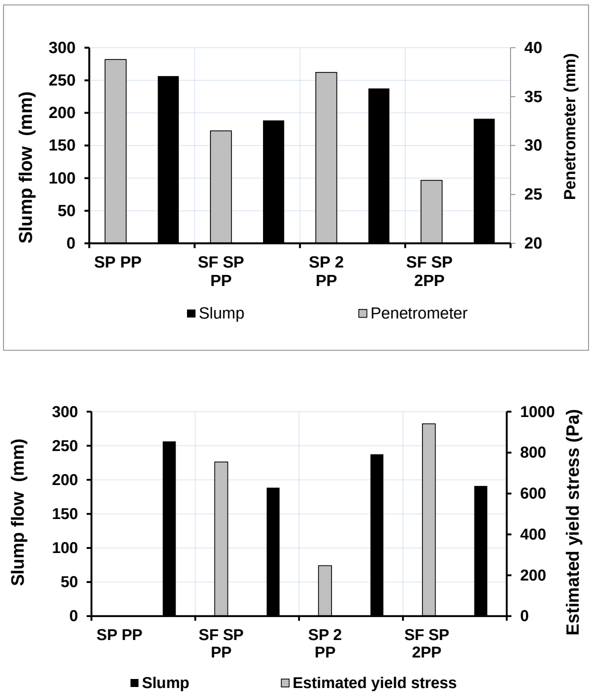


Fig. 7: Effect of SF on slump flow diameter, penetration and estimated yield stress

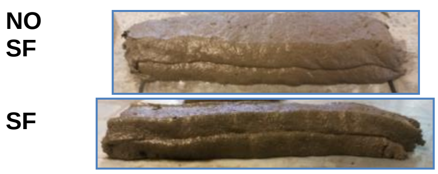


Fig. 8: Photos of layers made with and without SF

4.2 Effect of fibres on fresh and rheological properties of printed layers

Fig. 9 shows a reduction of the slump flow with the increase of the percentage of fibres (PP) from 0.2% to 0.6%. Furthermore, the results also indicate an increase of the static yield stress by increasing percentage of PP (particularly from 2PP to 3PP). It can be noticed that increasing the fibres enhanced the cohesiveness which limits significantly the flow of the mix and has an influence on its workability [Martinie 2009] [Kaci 2011]. With addition of 0.6%PP fibres, its volume becomes important due to its low specific gravity and has an impact on the consistency and on the flowability of the mix. Indeed fibres begin to connect and a process of percolation can occurs [Peled 2003].

The results of the penetrometer might indicate basically the same penetration with the addition of 0.4% fibres (2PP). However, a significant difference can be noticed when 0.6% of PP fibres (3PP) was added (Fig. 9). The results of the penetrometer might highlight that the network of PP fibres begin to be efficient at 0.6%PP (3PP) fibres to resist to this type of load due to the penetration of plunger.

Adding fibres permitted to the mix to have a better cohesiveness and have a more stable structure to not collapse under layer own weight and other successive layers.

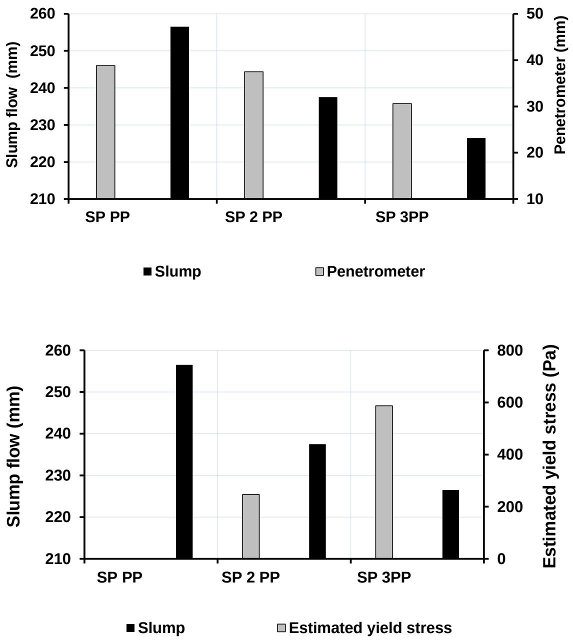


Fig. 9: Effect of PP fibres on slump flow diameter, on penetration and estimated yield stress

4.3 Effect of chemical admixtures on fresh and rheological properties of printed layers

4.3.1 - Superplasticiser

As expected, Fig. 10 shows a decrease of the slump flow with the reduction of % of SP from 0.55% (SP) to 0.275% (1/2SP). Additionally, it can be noticed an increase in a static yield stress (247-967 and 587-1079 Pa) with the reduction of SP for both mixes made with 2PP and 3PP, respectively. The very high value of spread diameter (around 240mm) is due to the addition of 0.55% of superplasticiser. An increase of SP has a significant influence on consistency and workability due the steric repulsion mechanism of SP. Indeed high dosage of SP can induced mixes segregation and bleeding [Sonebi 2015] [Puertas 2015] [Sonebi 2003].

The results of the penetrometer have the same trend compared to the results of slump flow as it can be noticed in Fig. 10. The penetrometer decreased when SP reduced from 0.55 to 0.275%. Penetrometer results confirm the influence of the effect of superplasticiser on consistency and flow ability.

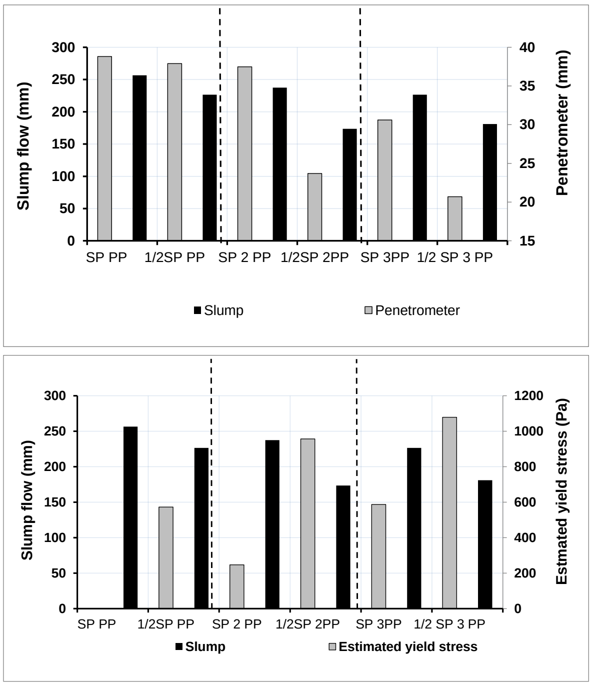


Fig. 10: Effect of SP on slump flow diameter, penetration test and estimated yield stress

4.3.2 – Effect of VMAs

The results in Fig. 11 show that the addition of diutan gum VMA1 at 0.05% for a given dosage of SP (0.5%) decreased significantly the slump flow. In parallel, an increase of the static yield stress with the addition of 0.05% of VMA1 can be noticed (Fig. 12, almost from zero to 900 Pa). The flow ability and segregation are reduced and the cohesion is enhanced due to the entanglement and intertwining of VMA1 polymer chains at low shear rate. The association of water between adjacent chains allows the decrease of the bleeding. At a dosage of 0.05%, VMA1 influenced radically the consistency, the yield stress, the cohesiveness and increase the viscous behaviour of the mortar [Schmidt 2013] [Sonebi 2006] [Sonebi 2003].

The results of the penetrometer have the same trend compared to the results of slump flow as it can be noticed in Fig. 11. It indicates a reduction in the penetration values with the addition of VMA1. Penetrometer results confirm the influence of the effect of diutan gum on consistency and flowability.

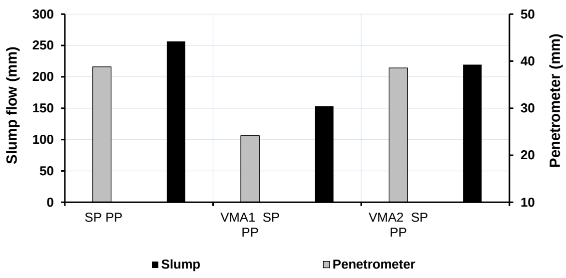


Fig. 11: Effect of VMAs on slump flow and penetration

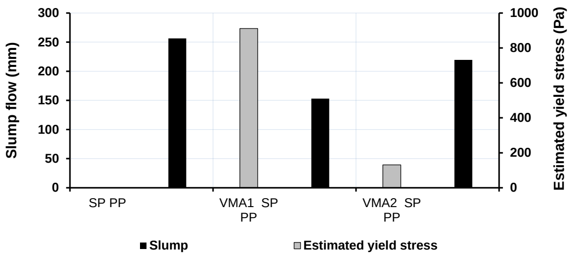


Fig. 12: Effect of VMAs and slump flow and estimated yield stress

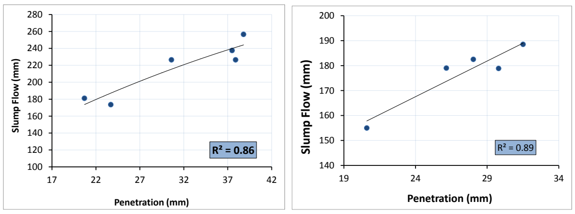
Fig. 11 shows that the addition of nano-clay gel VMA2 for a given dosage of SP decrease the slump flow. Additionally, an increase of the static yield stress (almost from zero to 131 Pa) with the addition of 0.1% of VMA2 can be observed (Fig. 12). Indeed, the particle size of nano-clay is significantly finer than those of cement and fly ash. Consequently, particles are inter mingle with the binder which increase the number of physical contact points and lead to enhance shear resistance. In addition, nano-clay increases the flocculation strength of the suspension which improved the structural stability. Additionally, cohesiveness of the mix is improved with the addition of nano-clay [Nathan 2010] [Kim 2010].

The reduction of the slump flow was about 41% with VMA1 compared to 15% with VMA2. Therefore, VMA1 is more powerful of reducing the fluidity. This difference could be explained by the type of mechanism and dosage of VMA. VMA1 caused an important loss of workability which influences the passing ability of the mix through the extruder. Therefore, VMA2 might be better solutions which improved the stability of the structure without decreasing dramatically the workability. The results of the penetrometer indicate slightly the same penetration with the addition of VMA2.

4.4 Correlation

Both slump flow and penetrometer test can measure the consistency of mortar. Consistency of mortar is a measure of its deformability when subjected to a certain type of stress. A correlation between slump flow and the penetrometer values were established for similar mortar.

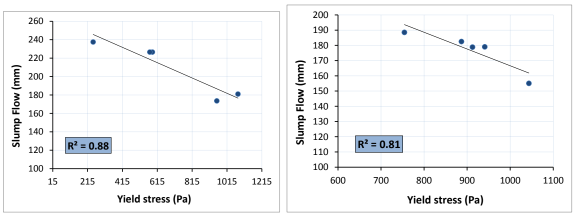
Fig. 13 shows a very good linear correlation between the slump flow and the penetrometer tests (R^2 = 0.86 and 0.89) of mixes made with different dosages of PP and SP (Fig. 13(a) and with SF (Fig. 13 (b)). It can be seen that the increase in slump flow led to an increase in penetration result.



(a) (b)

Fig. 13: Relationship between slump flow and penetrometer (a) (different PP and SP), (b) (with and without SF)

Additionally, as it can be observed in Fig. 14, the coefficients of correlation R^2 between slump flow and the estimated yield stress were about 0.88 and 0.81 for similar mortars. The relationship seemed to follow the linear model and showed that when the spread diameter decreased, the static yield stress increased. Even if the effect a constant energy was supplied to the mix, a good correlation between estimated static yield stress and slump flow was highlighted.



(a) (b)

Fig. 14: Relationship between yield stress and slump flow (a) (different PP and SP), (b) (with and without SF)

4.5 Opening time

Time gap represents the time period in which the mortar is still reasonably workable and extrudable in layers. The change of workability with time was measured using the flow table test and slump of cylinder test (to estimated yield stress). The extrudability was tested in extruding layers with a simple modified joint gun.

4.5.1 - Effect of fly ash

The open time was investigated mortar made with FA compared to NO-FA. As expected Fig. 15 shows that the addition of fly ash affect the time gap of the mix due to the pozzolanic behaviour of fly ash which didn't react in early hours. The consistency of the mix made with fly ash maintained the opening time after two hours compared to NO-FA (9% drop for fly ash compare to 24% for NO-FA). A drainage occurred during the extrusion for mix 100%C which had the consequence to not be extrudable after 55 min while it was still fluid. Adding fly ash improved the extrusion ability; maintain the consistency and the workability of the mix.

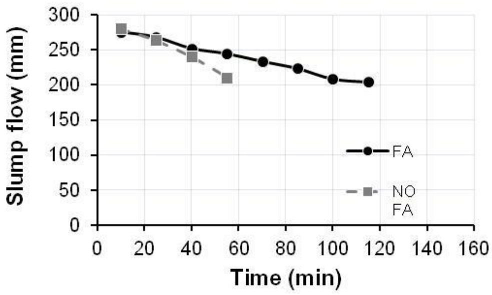


Fig. 15: Effect of FA on the opening time

4.5.2 - Effect of silica fume

Analysing Figs. 16 and 17, it can be observed that adding SF reduced dramatically the consistency and the workability and increase the yield stress during the time due to it's the high reactivity and cohesiveness. Indeed, it can be noticed a decrease of 75 min (PP) and 45min (2PP) of the time gap comparing mix with SF and without silica fume. An increase of the slope of the mix with SF can be noticed for the slump flow (8% drop without SF vs. 15% with SF) and estimated yield stress (17% drop without SF vs. 22% with SF).

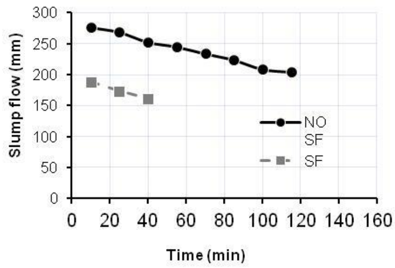


Fig. 16: Effect of SF on opening time (Slump flow vs. time)

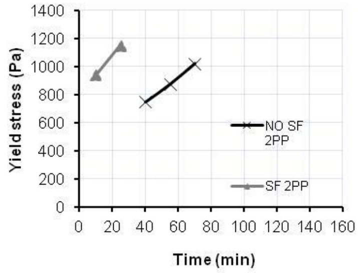


Fig. 17:Effect of SF on opening time (Yield stress vs. time)

4.5.3 - Effect of PP fibres

Fig. 18 indicates that the increase of polypropylene fibres at 0.6% PP(3PP) resulted in none- extrudable of mortar after 10 min of the open time test. It can be noticed a decrease of 45 min with the addition 0.4% of PP (2PP) and a reduction of 100 min with the addition of 0.6% of PP(3PP). An increase of the slope of the mix can be noticed with the increase of the dosage in fibres (15% drop with PP vs. 30% with 2PP). With time, a denser fibres network combined with the build-up rate of the cementitious mix induced a loss of workability and increased the difficulty of extrusion and caused drainage and a stiffening of the mortar.

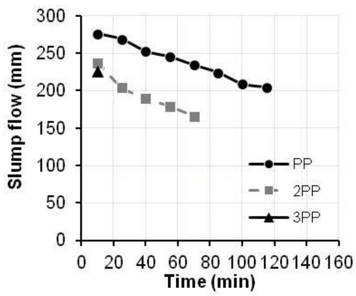


Fig. 18: Effect of PP (2PP, 3PP) on opening time (slump flow vs. time)

4.5.4 - Effect of SP

Opening time was investigated with variation of SP 0.275 to 0.55% (1/2SP & SP). Fig. 19 shows that the increase of SP influenced significantly the slump flow and the time gap of the mix. Indeed, it can be noticed a reduction of 30 min (PP) and 60 min (2PP) when SP increased from 0.55 to 0.275%. The decrease of SP led to an increase in the estimated yield stress and a reduction of time gap of 60 min (Fig. 19). Indeed SP which cause segregation, bleeding of water content and at this dosage might has a slight initial retardation of cement hydration might be the cause of this increase of time gap when superplasticiser dosage is increased (19% drop with SP vs. 21% with 1/2SP) [Puertas 2015].

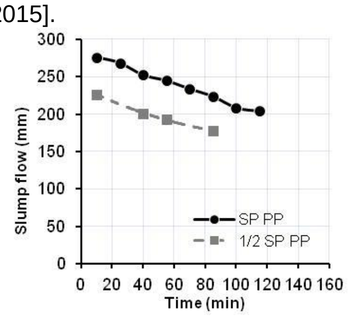


Fig. 19: Effect of SP on the opening time

4.5.5 - Effect of VMAs

The results show that the addition of diutan gum (VMA1) for a given dosage of SP (0.55%) decreased dramatically the open time of the mortar (Fig. 20). It can be noticed a decrease of 105 min with the addition of VMA1 (at 0.05%). Polymer chains of VMA1 enhance the cohesive force, viscosity and yield stress which lead to a decrease of flow ability, segregation and bleeding [Sonebi 2010] [Sonebi 2006]. Action of VMA1 combined with built up rate of the cementitious mix reduced the time gap.
The addition of 0.1% of nano-clay (VMA2) showed a decrease of the open time of 50 min which half lower compared to the results of VMA1. It can be noticed an increase of the slope of the open time with the addition of VMA2 which means that the addition of VMA2 increased the velocity of the loss of workability of the mix in time compared to NO-VMA mix (11% drop without VMA2 vs. 24% with VMA2) [Van der Vurst 2015] [Quanji 2010]. Particles filler behaviour increased the cohesiveness and enhance shear resistance (yield stress). In addition, nano-clay increased the viscosity and the flocculation of the suspension which improve the structural stability. Therefore, VMA2 behaviour combined with built up rate of the cementitious mix reduced the time gap.

Due to the round shape and small particle size distribution of VMA2, it allowed a better flowability and passing ability through the orifice of the gun than VMA2 and permitted a better extrusion and greater open time.

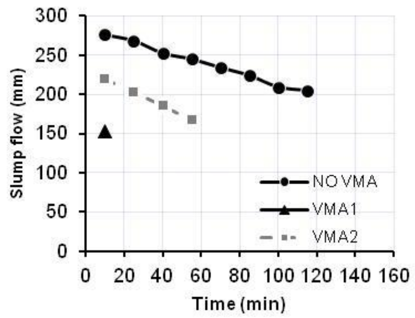


Fig. 20: Effect of VMA1 and VMA2 on the opening time

5 CONCLUSION

The objective of this paper was to study the effect of different mix compositions on the rheological behaviour and fresh properties of a printable mortar. Layers are extruded with a simple modified joint gun. This tool permitted in association with the slump test to determine the time gap and the extrudability of the different mixes. Based on the results from this study, the following conclusions can be made:

- The addition of 24% of fly ash (FA) and 8% of silica fume (SF) increased significantly the yield stress, cohesiveness, structure homogeneity and the stability appeared to be an advantage to print layers. Indeed it also reduced significantly the fluidity, the bleeding and the segregation of layers. Similarly, FA and SF reduced the slump flow. Additionally, it improved the passing ability through the extruder and showed a greater resistance to penetration. Using SF and FA led a reduction of time gap.
- Adding polypropylene (PP) fibres (0.2% to 0.6%) permitted to the mix to have a higher yield stress, cohesiveness and resulted in more stable structure to not collapse under own weight of layer and successive layers weight. With the incorporation of fibres the time gap is reduced. Furthermore, positive effect of fibres can be reversed when the percentage is too high (difficulties to extrude and drainage phenomenon which led to a stiffening of the mix). Polypropylene fibres might be efficient to print layers due to their length and diameter which led to a dense and efficient network.
- The addition of VMA permits to the mortar to gain in cohesiveness, in shear strength avoiding bleeding and segregation which is an advantage for 3D printing. However, the type and dosage of VMA is very important. VMA1 caused an important loss of workability and time gap which influenced the passing ability of mortar through the extruder. Therefore, VMA2 demonstrated a better performance which improved the stability of the structure without decreasing dramatically the workability and time gap. Moreover increasing SP

improved the workability, the passing ability through the extruder and led to a greater workability and penetration. However high dosage of SP increased risk of bleeding and segregation of the mix.

- A good linear correlation (R^2> 0.86) between penetrometer and flow table results was obtained. In addition, it might be noticed a good correlation (R^2>0.81) between the flow table and the estimated yield stress. Correlations showed that when the workability reduced, the static yield stress increased.

6 REFERENCES

[Alec 2016] Alec , Exquisite 400 m2 villa 3D printed on-site in Beijing in just 45 days, Article from the 3ders website, Jun. 2016, http://www.3ders.org/articles/20160614-exquisite-400-m2-villa-3d-printed-on-site-in-beijing-in-just-45-days.html (2016).

[Kaci 2011] Kaci A., Bourasa R., Phana V.T., Andréanib P.A., Chaouchea M., Brossas H., Adhesive and rheological properties of fresh fibre-reinforced mortars, Cement & Concrete Composites, 33, 2011, 218–224.

[Khoshnevis 2006] Khoshnevis B, Mega-scale fabrication by contour crafting, Department of Industrial and Systems Engineering, University of Southern California, Los Angeles: Int. J. Industrial and Systems Engineering, 1(3), 2006, 301-320.

[Kim 2010] Kim JH., Beacraft M., Shah SP., Effect of mineral admixtures on formwork pressure of self-consolidating concrete, Cement & Concrete Composites, 32(9), 2010, 665-671.

[Le 2012] Le TT.; Austin SA.; Lim S, Buswell, RA.; Gibb AGF.; Thorpe T.; Mix design and fresh properties for high-performance printing concrete. Mater and Structure, 45(8), 2012, 1221–1232.

[Lloret 2015] Lloret E., Shahab AR., Linus M., Flatt RJ., Gramazio F., Kohler M., Langenberg, S. Complex concrete structures – Merging existing casting techniques with digital fabrication, Computer-Aided Design 60(2015) 40-49.

[Maleab 2015] Malaeb Z., Hachem H., Tourbah A., Maalouf T., El Zarwi N., Hamzeh F., 3D Concrete printing: machine and mix design, Journal of Civil Engineering and Technology, 6(6), 2015, 14-22.

[Martinie 2010] Martine L., Rossi P., Roussel N. Rheology of fiber reinforced cementitious materials: classification and prediction, Cement and concrete research, 40 (2), 2010, 226-234.

[Nathan 2010] Nathan A. Tregger, Margaret E. Pakula, Surendra P. Shah, Influence of clays on the rheology of cement paste, Cement and Concrete Research, 40(3), 2010, 384-391.

[P. 3D] Contour Crafting : Votre maison imprimée en 3D," Primante 3D, 21 Janvier 2014. [Online]. Available: http://www.priximprimante3d.com/habitation/. [Accessed 25 October 2015].

[Pashias 1996] Pashias N et al, processing Effects in Cementitious Composites: Extrusion and Casting, Journal of Rheology, 40(6)1996, p. 1179-1189.

[Peled 2003] Peled A., Sha SP., P*rocessing Effects in Cementitious Composites: Extrusion and Casting*, Journal of materials civil engineering, 15(2) 2003, 192-199.

[Perrot 2015] Perrot A.; Rangeard D., Pierre A., Structural built-up of cement-based materials used for 3D- printing extrusion techniques. Materials and Structures, 49, 2015, 1213-1220.

[Puertas 2005] Puertas F., Santos H., Palacios M. and Martınez-Ramırez S., Polycarboxylate superplasticiser admixtures: effect on hydration, microstructure and rheological behaviour in cement pastes, Advances in Cement Research, 17(2), 2005, 77-89.

[Quanji 2010] Quanji Z., Thixotropic behavior of cement-based materials: effect of clay and cement types, Iowa State University , PhD Thesis, 2010, 144 p.

[Schmidt 2013] Schmidt W., Sonebi M., Brouwers, H.J.H. Jos, Kühne H-C., Meng B., "Rheology Modifying Admixtures: The Key to Innovation in Concrete Technology – A General Overview and Implications for Africa", Chemistry and Materials Research, Vol. 5, 2013, p. 115-120.

[Sonebi 2010] Sonebi M., Optimization of Cement Grouts Containing Silica Fume and Viscosity Modifying Admixture", ASCE Materials Journal in Civil Engineering, 22(4), 2010, 332-342.

[Sonebi 2006] Sonebi, M., Rheological Properties of Grouts with Viscosity Modifying Agents as Diutan Gum and Welan Gum Incorporating Pulverised Fly Ash, Cement and Concrete Research, 36 (9), 2006, 1609-1618.

[Scot 2016] C. Scott, Chinese Construction Company 3D Prints an Entire Two-Story House On-Site in 45 Days, Article from the 3DPrint website, Jan. 2016, https://3dprint.com/138664/huashang-tengda-3d-print-house/ (2016).

[Van der Vurst 2015] Van Der Vurst F., Grünewald S., De Schutter G., The impact of VMA on the Rheology, thixotropy and robustness of self-compacting mortars, RILEM 1st International Conference on Calcined Clays for Sustainable Concrete, Vol 10, 2015, p. 159-167.

[Wangler 2016] T. Wangler T, E. Lloret, L. Reiter, N. Hack, F. Gramazio, M. Kohler, M. Bernhard, B. Dillenburger, J. Buchli, N. Roussel, R. Flatt, Digital Concrete: Opportunities and Challenges, RILEM Technical Letters 1, 2016, 67-75.